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# MarcoPolo-R: Near Earth Asteroid Sample Return Mission Selected for the Assessment Study Phase of the ESA program Cosmic Vision

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**Abstract.** This paper presents the sample return mission to a primitive Near-Earth Asteroid (NEA) MarcoPolo-R proposed to the European Space Agency in December 2010. MarcoPolo-R was selected in February 2011 with three other missions addressing different science objectives for the two-year Assessment Phase of the Medium-Class mission competition of the Cosmic Vision 2 program for launch in 2022. The baseline target of MarcoPolo-R is the binary NEA (175706) 1996 FG3, which offers an efficient operational and technical mission profile. A binary target also provides enhanced science return. The choice of a binary target allows several scientific investigations to occur more easily than through a single object, in particular regarding the fascinating geology and geophysics of asteroids. MarcoPolo-R will rendezvous with a primitive, organic-rich NEA, scientifically characterize it at multiple scales, and return a bulk sample to Earth for laboratory analyses. The MarcoPolo-R sample will provide a representative sample from the surface of a known asteroid with known geologic context, and will contribute to the inventory of primitive material that is probably missing from the meteorite collection. The MarcoPolo-R samples will thus contribute to the exploration of the origin of planetary materials and initial stages of habitable planet formation, to the identification and characterization of the organics and volatiles in a primitive asteroid and to the understanding of the unique geomorphology, dynamics and evolution of a binary asteroid that belongs to the Potentially Hazardous Asteroid (PHA) population.

**Keywords:** Astrobiology – Near-Earth Asteroid - Origin – Primitive material– Sample Return Mission – Re-entry capsule.

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## 1. Introduction

Primitive asteroids provide windows into the nature of the raw materials from which the Earth and other terrestrial planets formed, as well as the processes of planet formation [1]. In addition, they retain material that predates the Solar System [2, 3] and contains evidence for interstellar processes and its original formation in late-type stars (e.g. [4]). According to current exobiological scenarios, an exogenous delivery of organic matter may have contributed to the emergence of life: primitive bodies that collided with our planet in the early phases of our Solar System may have delivered the complex organic molecules and triggered the pre-biotic synthesis of biochemical compounds [5, 6]. Moreover, because collisions of Near-Earth Asteroids (NEAs) with the Earth still pose a finite hazard to life, it is important to improve our knowledge of the properties of these bodies. Space missions devoted to the exploration of these bodies are thus extremely needed.

The small sample successfully returned by the JAXA Hayabusa mission is confirmed as originating from a highly processed S-type asteroid [7]. Then, the sampling provided by meteorites may not offer the most primitive material available in near-Earth space. Indeed, meteorite samples are altered by the processes of ejection from their parent body and by atmospheric entry. Furthermore, meteorite samples are quickly subjected to contamination by terrestrial microbes. As an example, the possible presence of extraterrestrial RNA nucleobases in the carbonaceous Murchison meteorite has been debated for decades because of likely contamination from terrestrial DNA and RNA [8, 9]. Despite the issue of contamination, there is now strong evidence that nucleobases are actually present in some meteorites of primitive class [10, 11]. This even strengthens the motivation to return primitive samples in order to unambiguously assess the presence of nucleobases on primitive asteroids and to better understand the role of primitive material in nucleobases delivery (and possibly in the emergence of life). It is only by studying the organic chemistry and geochemistry of a pristine carbonaceous asteroid sample that the nature of extraterrestrial organic compounds can be understood.

The high international interest for sample return missions to primitive asteroids is demonstrated by their recent selections by leading space agencies. NASA selected the OSIRIS-REx mission in spring 2011 in the New Frontiers program for launch in 2016 and a return from the B-type NEA (101955) 1999RQ36 to Earth in 2023. The Hayabusa 2 mission is now in phase B at JAXA for launch in 2014 and a return from the C-type NEA (162173) 1999JU3 to Earth in 2020. Both missions will allow us to improve greatly our knowledge of the material composing primitive asteroids. However, it is important that several such missions are sent to different objects using different sampling approaches in order to eventually achieve a comprehensive knowledge of primitive materials. Indeed, the recent experience of the Sudan meteorite Almahata Sitta, resulting from the impact of the NEA 2008 TC3, showed us that small bodies are probably more complex and diverse than originally thought, and emphasizes the uncertainty and incompleteness of our understanding. This fall is the first instance where an object was observed astronomically as an asteroid and then was recovered as meteorite samples. It was identified as an F-class object, similar to C-class (bluer in the visible), but the meteorites are unexpectedly friable breccias of mostly ureilite and enstatite chondrite clasts [12, 13]. The recovered meteorites represent only 0.005% of the initial mass [12], which demonstrates that mechanically weak material does exist in significant quantities within the inner Solar System and that the existing meteorite collection is significantly biased towards heavily processed material.

The main goal of the MarcoPolo-R mission is to contribute to the knowledge of primitive material by returning unaltered material from a primitive NEA for detailed analysis in ground-based laboratories. MarcoPolo-R will allow us to study the most primitive materials available to investigate early Solar System formation processes, returned from a known target with known geological context. Moreover, it will have an increased science thanks to the choice of a binary object as its baseline target. MarcoPolo-R will provide scientific results that are crucial to answer the following key questions:

1. What were the processes occurring in the early Solar System and accompanying planet formation?
2. What are the physical properties and evolution of the building blocks of terrestrial planets?
3. Do NEAs of primitive classes contain pre-solar material yet unknown in meteoritic samples?
4. What are the nature and the origin of the organics in primitive asteroids and how can they shed light on the origin of molecules necessary for life?

Remote sensing gives only the most superficial information on the surface composition. The already mentioned spectral observations of asteroid 2008 TC3 and the analysis of fragments recovered on Earth provide evidence that there is a discrepancy between the expected composition of a small body based solely on its spectral properties and the actual one from recovered fragments [12]. Moreover, in-situ measurements that can be made by a lander are interesting but severely limited by the resources available.

Consequently, answers to these fundamental questions require measurements with exceptionally high precision and sensitivity. Sample returned to terrestrial laboratories, which are unconstrained by mass, power, stability etc. are definitely required. In particular, laboratory techniques can date the major events in the history of a sample and investigate the organic components.

Cosmic Vision 2015-2025 roadmap lays out four fundamental questions to be addressed by ESA's mission program. For the second of these, "How does the Solar System work?", it states: "The natural next step in ESA's exploration of small Solar System bodies would be a sample return mission of material from one of the near-Earth asteroids." Sample return from a primitive NEA also addresses the Cosmic Vision question "What are the conditions for life and planetary formation?"

NEAs are among the most accessible bodies of the solar system. For several tens of NEAs, the velocity impulse ( $\Delta v$ ) required to transfer and insert a spacecraft in orbit around them is lower than that required for the Moon.

The MarcoPolo-R mission is based on the previous Marco Polo mission, which was selected in the ESA Cosmic Vision 1 program in 2007. Its scientific rationale was highly ranked by ESA committees, but its estimated cost exceeded the allotted amount. The cost of MarcoPolo-R can be reduced by a better optimization of the mission design and possible international collaborations.

The baseline target of MarcoPolo-R, the binary NEA (175706) 1996 FG3, offers an efficient operational and technical mission profile. The choice of this target will allow us to obtain information that cannot be obtained from a single object and enables investigations of the fascinating geology and geophysics of asteroids (see Sec. 6). Several launch windows have been identified in the time-span 2020-2024. Possible back up targets of high scientific interests have been identified and current studies look for adapted mission scenarios. Hence the MarcoPolo-R samples will allow us to:

- explore the origin of planetary materials and initial stages of habitable planet formation;
- identify and characterize the organics and volatiles in a primitive asteroid;
- understand the unique geomorphology, dynamics and evolution of a binary NEA.

Two industries have started the assessment study of the mission in February 2012 for one year. All parts of the missions are considered, although technology activities are already ongoing or about to start soon in specific areas, e.g. an additional study entirely focused on the sample mechanism starts in July 2012.

So far, the baseline mission scenario of MarcoPolo-R to 1996 FG3 is as follows: a single primary spacecraft, carrying the Earth Re-entry Capsule and the sample acquisition and transfer system, will be launched by a Soyuz-Fregat rocket from Kourou. Two similar missions with two launch windows, in 2021 and 2023 and a sample return as soon as in 2029, have been defined. Earlier or later launches, in 2020 or 2024, also offer good opportunities. Both chemical and electrical propulsion systems are considered in the current study, and the final choice will depend on the outcome of the study. In the following, we briefly describe the current advances (spring 2012) of the MarcoPolo-R mission study (see [14] for more details on the original proposal and payload elements).

## **2. Mission Profile**

There is a wide range of options available when defining a mission profile for an asteroid sample return mission. Mission design choices must take into account the main constraints and design implications, which for MarcoPolo-R are:

- Preferred target: the binary 1996 FG3
- Launch vehicle: Soyuz/Fregat
- Minimum stay time at the asteroid: 3-6 months
- Maximum entry velocity:  $12-13 \text{ km.s}^{-1}$ , limited by the Earth Re-entry Capsule (ERC) heat-shield material capabilities.

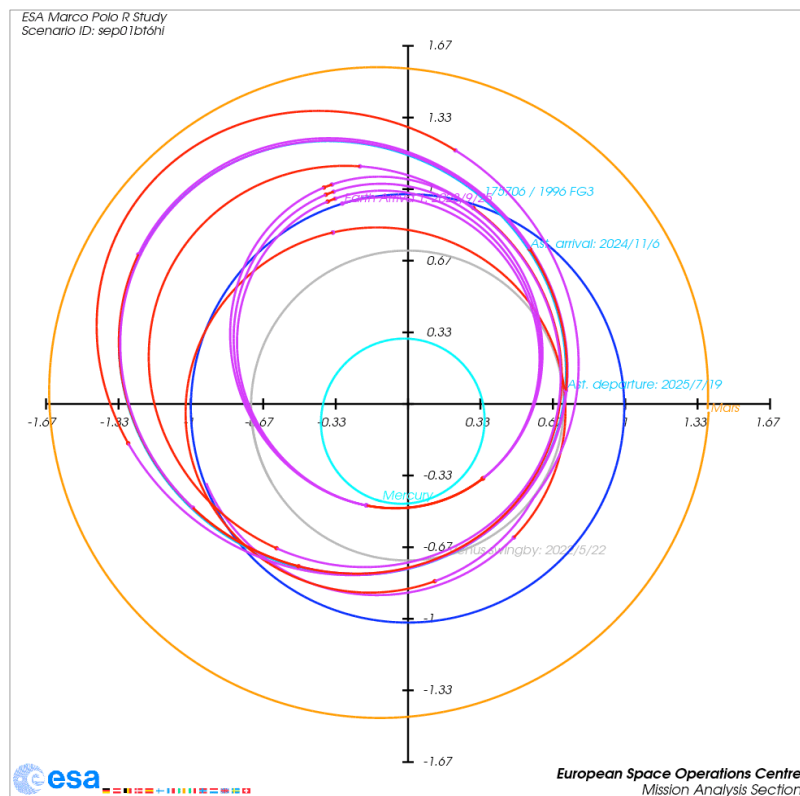
### **2.1 Launcher requirements**

For the preferred target and selected launch vehicle, feasible missions can be found using chemical propulsion by launching into Geosynchronous Transfer Orbit (GTO) and using two space segment stages or electric propulsion by launching directly into the correct interplanetary trajectory. The use of a GTO launch with a large propulsion capability enables more mass to be delivered to the asteroid but requires a large propulsion system and possibly an extra propulsion module. Besides the mission scenario, in this case, leads to a rather long 10-year mission. Electric propulsion offers attractive alternatives to the chemical one (lower escape velocity, no

planetary assist). It may allow a decrease of the mission duration (and associated operation costs) and an increase of the possible carried mass. A detailed study of both propulsion systems will allow determining which is the most suitable. In the preliminary mission definition phase however, an electric propulsion scenario has been developed and is presented here.

## 2.2 Orbit requirements

Several potential mission scenarios were identified within the 2020-2024 launch timeframe. The mission will be launched from Kourou on board a Soyuz/Fregat launcher. Figure 1 shows an overview of the baseline mission using an electrical propulsion system. The industry study will probably lead to a slightly different mission scenario but it should not change the different steps of the missions as describe in this paper. The electric engines will provide the velocity impulse ( $\Delta v$ ) to reach the target via planetary fly-bys of Venus. This will be followed by the asteroid approach phase during which the spacecraft will perform the targeting maneuvers required to rendezvous with the asteroid.



**Figure 1.** Example of MarcoPolo-R trajectory with launch in April 2021 (ESA).

When the spacecraft is close enough to the asteroid, the interplanetary cruise ends and the approach phase begins. An on-board star sensor or narrow angle camera is used to detect and track the NEA. Some braking maneuvers are executed to reduce the approach velocity and increase the knowledge of the spacecraft relative state with respect to the asteroid. This phase typically lasts one month.

When the spacecraft is at a few tens of km from the asteroid, the proximity operations start. The first sub-phase of the proximity operations is Far Station Keeping. The on-board Guidance Navigation Control/Attitude and Orbit Control System/Failure Detection, Isolation and Recovery (GNC/AOCS/FDIR) system has been developed in a Technology Research Program activity at ESA led by GMV Company (called NEO-GNC).

This technique assures safe station keeping using a wide-angle camera. Only light curves taken from ground observatories (prior to launch) and refined using on-board observations during the approach phase are needed.

During this phase, enough time to observe a large portion of the surface of the asteroid should be allocated (~1 month). To ensure good visibility of the asteroid, the Far Station location should be close to the Sun-asteroid line. Several station positions at closer distances are foreseen, that allow a better characterization and eventually a more precise estimate of the gravity parameters of the asteroid.

When the distance is close enough, the spacecraft can be injected into a Self-Stabilised Terminator Orbit (SSTO), which requires very sparse maneuvers for perturbation control. The duration in this phase shall allow for radio science experiment and for identification of the landing site. Remote sensing activities are performed, characterizing the asteroid in different levels of detail and determining its main gravitational, thermal and topographic characteristics. Local characterization shall be performed for some potential landing sites. After a landing site is selected, the Descent & Landing phase (D&L) can start. Up to three sampling attempts are considered. The D&L can be preceded by some rehearsals, which are essentially a D&L procedure stopped at a certain altitude. The spacecraft will follow a predefined descent profile that fulfils all constraints to achieve safely the required landing accuracy. At a given altitude, the spacecraft shall perform the D&L phase autonomously.

After touch-down, the surface operations shall start, beginning with the spacecraft stabilization, then execution of the sampling phase, transfer of the collected material to a canister inside the ERC and the ascent phase, which ends when the spacecraft is in the desired safe haven. From this point, the mission can perform additional science observations and prepare for the return flight (inbound trajectory).

The spacecraft will be injected on to the return trajectory ending with ERC release and Earth atmospheric entry.

### **3. Model payload**

#### **3.1. *Nominal payloads***

As requested for an M class mission, the proposed instruments are based on existing/under development technologies (Technological Readiness Level  $\geq 4$ ), and have already been assessed as a result of the assessment study phase of the former Marco Polo Mission in 2008-2009; details of the payloads can be found in the Payload Definition Document (PDD; see the ESA web site: <http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=49580#>). The nominal payload includes a Wide Angle Camera (WAC), a Narrow Angle Camera (NAC), a Close Up Camera, a Visible Near-Infrared Spectrometer, a Mid-Infrared Spectrometer, a Radio Science Experiment and a Neutral Particle Analyser. Since the main differences between the former Marco Polo mission and MarcoPolo-R are the choice of a binary asteroid as the baseline target and launch years, the characteristics of the instruments and key-resources remain essentially the same and therefore we do not reproduce them here. All details can be found in the Marco Polo PDD and in [14]. All these instruments are defined based on the scientific requirements and associated measurements at the asteroid, which are structured in three phases: ‘global characterization’, ‘local characterization’, and ‘sample context measurements’:

- ‘Global characterization’ means to measure the properties of the whole NEA, on a global scale;
- ‘Local characterization’ is the characterization of dedicated areas that are identified as potential sampling sites;
- ‘Sample context measurements’ are measurements being performed at the actual sampling site.

The global characterization of the body is required to obtain as complete a picture as possible of the physical nature of the NEA in order to relate the properties of the sample to those of the parent body. Moreover, for the overall success of the mission, the global characterization will allow the selection of a number of surface areas as potential locations for the intended surface sampling.

#### **3.2 *Optional payloads***

Optional payloads have been identified that would provide additional science return. A Laser altimeter can be considered to measure the two-way travel time of a pulse between the instrument and the surface of the asteroid. A topographic profile along the ground track of the spacecraft can then be produced from which a global shape model can be derived (in conjunction with WAC and NAC images).

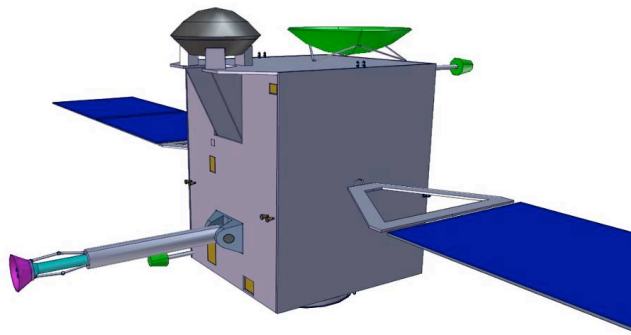
An optional lander package, with a total mass of about 10 kg, is also considered and has the means to characterize physical properties (e.g. electrical, magnetic, thermal) of its landing site, as well as the surface and subsurface fine structure and composition. Complementary data from a lander science package can address questions such as: are the returned soils and rocks representative of the bulk of the parent body? What are the macroscopic physical properties of the terrain from which the samples have been extracted? A lander could also

act together with the spacecraft to support the global characterization of the asteroid, e.g. by microwave sounding, and thus, enhance our understanding of the formation process of the target. A seismic experiment might also be considered that can provide information on the internal and surface properties of the asteroid.

## 4. System requirements and spacecraft key issues

### 4.1 System requirements

The science priorities and mission requirements for MarcoPolo-R can be met by a large number of mission architecture options which will need to be carefully analyzed and traded-off to select the optimal baseline. Although the current assessment study by industries may lead to new designs, a preliminary analysis was performed internally at ESA, based on electric propulsion, which has led to a feasible reference solution. The spacecraft design suggested by this internal study is shown in Figure 2.



**Figure 2.** Spacecraft design from the MarcoPolo-R Phase 0 study.

#### 4.1.1 Space segment mass budget

The analysis by the Concurrent Design Facility of ESA (CDF) found that a direct launch with electric propulsion can be performed with a main spacecraft of dry mass around 1100 kg and a re-entry capsule around 55 kg, including all margins. The resulting wet mass is around 1530 kg. Such a mission has a duration of 7.8 years for the baseline 2021 launch and 7 years for the backup 2023 launch. The stay time at the asteroid is 265 days in the baseline scenario and 190 days in the backup case.

The two industrial studies will review the choice of the propulsion system and confirm whether it is the most appropriate, accounting for the cost as well as the pros and cons of each system.

#### 4.1.2 Communication

The ground system assumed for the mission uses the ESA Deep Space Network (DSN). A 35 m ground station is baselined for nominal operations with availability for eight hours per day during proximity operations. A 70 m ground station can be made available in case of emergency. Requirements for the MarcoPolo-R communication subsystem include: telemetry and telecommand during all mission phases; peak data downlink during the remote sensing phase; navigation images during characterization and proximity operations and in-situ instrument data. The remote sensing phase is the most demanding in terms of required data rate. Therefore, the sizing of the communication subsystem is driven by the data rates and volume of that phase. For the appropriate range of distance of the spacecraft to the Earth, during the proximity operations, assuming a fixed High Gain Antenna (HGA) of diameter 1.4 m and a high output power transponder, a data-rate of 20 kbps can be sustained in X band. The baseline communication hardware includes a prime and redundant Low Gain Antenna, providing omni-directional coverage for Low Earth Orbit phase, a fixed HGA for the main data transmission, and a Medium Gain Antenna, providing useful telemetry during descent and landing and emergency communication in safe mode.



### 4.1.3 Power

The distance to the Sun during the proximity operations phase is between 0.7 and 1.42 AU, with the solar constant ranging between 2794 and 698 W.m<sup>-2</sup>. This leads to a significant solar array area of ~16 m<sup>2</sup>. There is no credible alternative to solar arrays in Europe in the mission timescale, so a large area of solar arrays will have to be accommodated. This will have implications for the spacecraft configuration.

Lithium Ion batteries are selected as the baseline. The sizing case (descent, sampling and ascent maneuvers) leads to an energy requirement of 1065 Wh resulting in a total battery mass of about 13 kg.

### 4.1.4 Thermal system

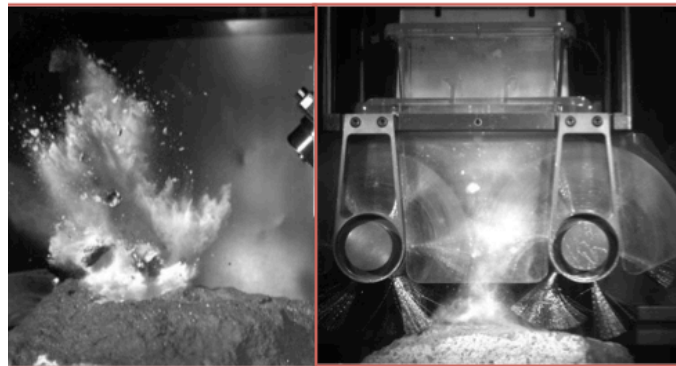
Radiations from the Sun and the asteroid (and Venus during the transfer phase) influence the thermal environment of the spacecraft. The most demanding phase for the thermal system is the landing phase where the spacecraft could need to operate on a surface at 190 °C. The proposed thermal design makes use of Multi-Layer Insulation, with some radiators to dissipate heat in particular from exposed components. Heaters are also needed to maintain the spacecraft temperature when in a cold environment or to compensate for any equipment that is not operating.

## 4.2 Landing, sampling and transfer systems

There are a number of options for the landing and sampling systems and the selected option has a strong influence on the spacecraft design.

The Science requirements for the sampling device are the following: it should have the capability to acquire a minimum mass of the order of a hundred grams and should return them to Earth; moreover, it should have the capability to acquire a selection of cm-sized fragments, plus a large number (minimum several grams) of small (hundreds of µm-sized to mm-sized) particles.

A Sample and Acquisition System (SAS) was proposed by the US partners in the MarcoPolo-R proposal (see [14]), in order to perform the sample acquisition, verification, and transfer into an ERC developed by NASA Langley Research Center (LaRC). The SAS comprised two arms (from the Jet Propulsion Laboratory, JPL), each with a Brush Wheel Sampler (BHW, from JPL), two rock chippers (from the Johns Hopkins University Applied Physics Laboratory, APL), a sample canister with a sample verification mechanism, and hinge latch and spin eject mechanisms (all from JPL). The BWS has been designed and tested to collect the required sample (between 0.35 and 2.1 kg) in less than one second. If the asteroid surface is assessed to contain no loose regolith, pyrotechnic rock chippers are fired during the sampling event. This determination is made prior to sampling and activated by ground command. The canister door is shut after two seconds of asteroid contact. The BWS can be reused in subsequent sample collections. The BWS has been tested in air and in vacuum, in Earth gravity and in low gravity on the Boeing KC-135A aircraft, with many regolith simulants, including one using the modified lunar regolith size distribution (Figure 3). Rock chipper testing with an operating BWS has demonstrated the capability to generate and collect 15g of sample per single rock chipper firing into Bandelier tuff rocks (two chippers are fired during a sample collection event).



**Figure 3.** Possible concept of a sampling device. Left: test with a Rock Chipper that has been shot; right: Brush Wheel Sampler and Bandelier tuff rocks.

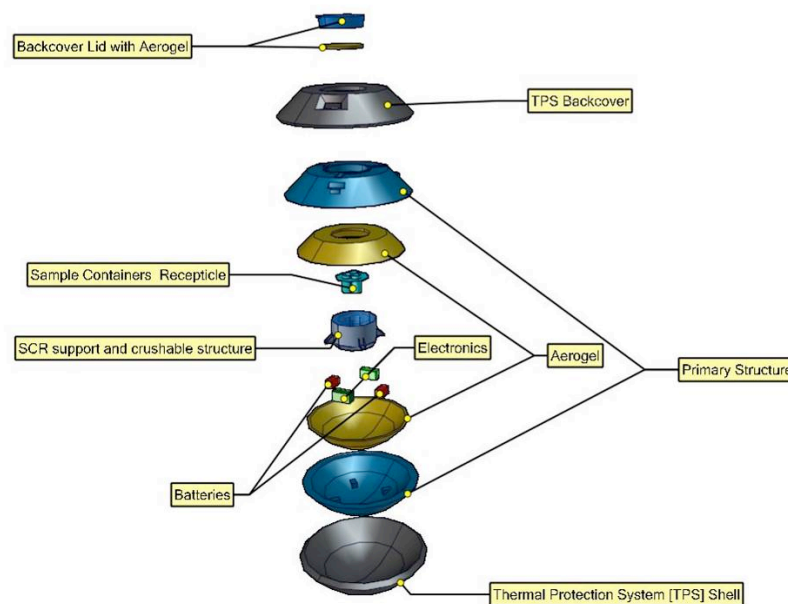


In the current study of a mission entirely developed by ESA, alternative sampling approaches are investigated by the two industries selected to perform the assessment study. Moreover an independent technical study will start in July 2012 concentrating on “Touch and Go” sampling mechanisms. Cutting wheels, scoops and gaseous transport devices are among the mechanisms that will be considered.

The ability to perform an efficient sampling of the surface and to return the minimum required amount of material is crucial for the success of the mission.

### 4.3 Earth Re-entry Capsule (ERC)

The design proposed for the MarcoPolo-R ERC is entirely passive. It does not make use of a parachute in order to save costs to the greatest extent and instead lands at around 45 m/s with the energy being absorbed at landing by a crushable structure. This parachute-less approach is derived from the Mars Sample Return (MSR) mission design. However, the planetary protection requirements for MarcoPolo-R are much less harsh and therefore such a capsule has a much simpler design than for MSR as no bio-container needs to be accommodated. This design (see Fig. 4) was optimized to meet MarcoPolo-R mission needs while preserving key characteristics for high reliability.



**Figure 4.** Illustration of possible MarcoPolo-R ERC (cross section).

The final configuration of the ERC, assumed at present to be developed in Europe, will depend on the study by the European industries.

## 5. Mission phases, operations, archiving, and Curation Facility

Currently, the following mission phases are foreseen, each accompanied with science operation activities that are described in [14]: near-Earth commissioning and calibration phase, cruise phase, asteroid phases, asteroid characterization phase, lander delivery phase (optional), “Touch and go” phase, lander relay phase (optional), in-situ measurements done by the Lander (optional), return cruise phase, Earth re-entry, sample distribution and ground measurement phase.

The aim of the mission operations is to assure the monitoring and the control of the complete mission. The control of the MarcoPolo-R mission will take place at ESOC.

The scientific data will be acquired during the NEA acquisition/approach, the near NEA phase before and during the optional lander delivery (and relay) phase, and after the sampling, during an extended monitoring

phase. Some cruise science will also be done with only a very small impact on operation cost. Particularly important are the operations governing the sample collection phases, the sample transfer to ERC, the round trip cruise phases and the ERC delivery. During critical mission phases (launch, cruise, sampling, Earth return, ERC recovery), support for tracking, telemetry and command by the ESA ground stations could be foreseen.

For the entire mission duration, ESA will provide facilities and services to the scientific experiment teams through a MarcoPolo-R Science Ground Segment.

While spacecraft operations end once the ERC has safely returned the samples to the surface of the Earth, a major phase of the overall mission remains before the sample science phase in the community can commence. Many different laboratories across Europe and around the world will be required to undertake the full range of studies necessary to answer the scientific questions MarcoPolo-R seeks to address. This demands that carefully selected portions of the returned material are identified and distributed to appropriate laboratories. A sample Receiving and Curation Facility is an essential element of the mission and is required for the long term archiving of such a valuable resource.

First and foremost, the facility must guarantee to preserve the sample in its pristine condition, avoiding chemical and physical alteration of materials by the Earth environments in order that none of the key analyses are compromised, ensuring the highest scientific return. The key activities of the facility are to provide:

- secure and appropriate long term storage,
- preliminary characterization of the sample,
- preparation and distribution of sub-samples,
- accurate documentation of the samples.

Considerable expertise exists within Europe for the curation and distribution of sensitive extraterrestrial samples – e.g. numerous large national meteorite collections, Antarctic meteorite collections and cosmic dust collection programs.

Presently, no single facility exists within Europe that has the capability to curate, characterize and distribute returned samples in the way required for this mission. In addition to the samples from the NEA, the Curation Facility will act as a repository and distribution centre for a further two sets of material that will be important in confirming that the samples have not been affected by contamination. The first set is of materials collected during the construction of the spacecraft that may contribute volatiles or directly contact the sample. The second set is of witness plates recording the sample collection process and sample storage that the ERC will return along with the NEA sample.

The new ESA centre at Harwell (UK) contains a proposed sample receiving facility (as part of Mars sample return), although a decision on whether this will go ahead (or indeed if it is appropriate for an asteroid sample return) has not yet been finalized and alternative sites within Europe may be equally viable. A description of the ground-based sample analysis that will be performed to reach the science objectives of MarcoPolo-R can be found in the assessment study report (called Yellow Book) of the former Marco Polo study (see the ESA web site: <http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=46019>).

## **6. Science value of a binary asteroid**

Binary objects represent about 16% of both the NEA and main belt populations [15] and their formation mechanism is still a matter of debate, although several scenarios have been proposed to explain their existence [16, 17]. In particular, rotational disruption of a rubble pile NEA as a result of spin-up above the fission threshold due to the YORP effect (a thermal effect which can slowly increase or decrease the rotation rate of irregular objects) has been shown to be a mechanism that can produce binary asteroids with properties that are consistent with the observed ones (shape of the primary, size ratio of the primary to the secondary and circular equatorial secondary orbit, [16]). Other fission scenarios have been proposed that imply different physical properties of the binary [17]. Binary formation scenarios therefore place constraints on, and implications for, the internal structure of these objects. One of the most important implications of the model by Walsh et al. [16] is that the pole of the primary should be composed of fresh material that was originally buried at some depth in the progenitor. In effect, in this model, when the progenitor is spun up, the material of the pole migrates to the equator and when the centrifugal force exceeds the gravity of the body, this material escapes from the surface to form the secondary (see Figure 5). According to this model, collecting samples from the pole of the primary can therefore provide a means of obtaining material that was originally inside the body without having to drill deeper.

Moreover, thanks to its binary nature, the sizes, mass and orbit pole direction of the system can be estimated from Earth-based observations. This knowledge of basic physical parameters will enhance navigation accuracy

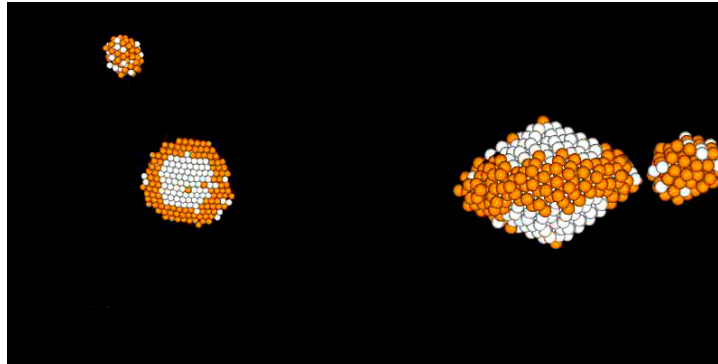
and lower mission risk during the rendezvous; it will reduce the time required for initial characterization before entering into close-in, bound orbits.

A visit to a binary system will thus allow several scientific investigations to occur more easily than through a single object, in particular regarding the fascinating geology and geophysics of asteroids:

1. Precise measurements of the mutual orbit and rotation state of both components can be used to probe higher-level harmonics of the gravitational potential, and therefore internal structure.

2. A unique opportunity is offered to study the dynamical evolution driven by the YORP/Yarkovsky thermal effects.

3. Possible migration of regolith on the primary from poles to equator allows the increasing maturity of asteroidal regolith with time to be expressed as a latitude-dependent trend, with the most-weathered material at the equator matching what is seen in the secondary.



**Figure 5.** Final snapshot of a simulation of binary formation by YORP spin-up (left: top view; right: side view); orange particles were originally located at the surface of the progenitor; white particles were originally below the surface. Note that the pole of the primary is essentially composed of fresh (white) material that was originally buried inside the progenitor [16]. This image is to be compared with the binaries observed by radars, such as 1999KW4 [18], whose properties resemble those produced by the simulation (e.g. oblate primary shape, secondary to primary size ratio, etc.).

Moreover, a sample return would bring us, in addition to the primitive materials discussed above, crucial information: i) that may allow discrimination between the most likely formation mechanisms, ii) about the internal composition of the progenitor (as part of the surface of the primary may well correspond to some material that was located in the interior of the progenitor).

## 7. Conclusion

MarcoPolo-R is one of the four candidates selected by ESA (February, 25, 2011) in the ESA M3 Cosmic Vision 2 program to proceed for an assessment study. The target cost for ESA is 470 Millions of Euros. The aim of the assessment study is to design the best mission to reach the science objectives, while keeping the budget below the cost limit.

In addition to addressing its exciting science goal, the MarcoPolo-R mission also involves technologies for which technical development programs are well under way. It is the ideal platform to (i) demonstrate innovative capabilities such as: accurate planetary navigation and landing, sample return operational chain; (ii) prepare the next generation of curation facilities for extra-terrestrial sample storage and analysis; (iii) pave the way as a pathfinder mission for future sample returns from bodies with high surface gravity. MarcoPolo-R will ensure that European laboratories involved in sample analysis remain world-class facilities spanning the entire breadth of expertise required for the science success of the mission. MarcoPolo-R will also involve a large community in a wide range of disciplines (Planetology, Astrobiology, Cosmochemistry, etc...) and will generate tremendous public interest.

The choice of a binary asteroid as the baseline target for the first time will provide enhanced science knowledge and complement in a unique way the science return of the two other sample return missions under development, namely the NASA OSIRIS-Rex and the JAXA Hayabusa 2 missions. The returned sample (first for ESA) will then be of inestimable value. Given the expected richness of small body compositions, until we return

a sample from various primitive asteroids, to which MarcoPolo-R will contribute, we will not achieve a comprehensive knowledge of primitive materials.

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